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Combination of Longitudinal Train Dynamics and Multibody Simulation: Comparison of Co-Simulation with Other Modelling Strategies

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Abstract

The present work aims to benchmark co-simulation architectures against other modelling strategies that can be adopted to combine longitudinal train dynamics and multibody simulations. The comparison of the modelling strategies is performed on a reference train-track operation scenario extracted from an international benchmark, building a detailed multibody model of a group of four wagons. The rest of the train composition is considered in the multibody environment with different approaches, namely a straightforward model applying the in-train forces obtained from a preliminary longitudinal train dynamics simulation, a mixed multibody model where the remaining wagons are modelled as single degree of freedom masses and a multibody model replacing wagon sets with a single big mass. It is found that the multibody models which do not need to exchange data with a separate longitudinal train dynamics module can easily consider the effect of the lateral component of the in-train forces on the derailment ratio, while ensuring lower times for the model setup and simulation with respect to co-simulation architectures.

Keywords: longitudinal train dynamics, multibody system dynamics, co-simulation, running safety, three-piece bogie, heavy haul, wheel-rail contact.

1 Introduction

The operation of long heavy-haul freight trains can generate large in-train forces on vehicle connection systems, particularly during traction and air brake manoeuvres in curved sections [1]. These forces generate vertical and lateral components, negatively affecting railway vehicle safety and stability and increasing the risk of derailment [2].

A thorough study of longitudinal train dynamics (LTD) [3 - 6] becomes imperative when analysing the full dynamics of isolated vehicles or small groups within the train. Typically, such analyses use multibody (MB) codes, that can effectively account for wheel-rail interaction and compute contact forces, which are required to determine the safety criteria defined in international rules. Conversely, LTD simulations for the evaluation of the in-train forces are commonly undertaken using standalone simplified codes [7], where each vehicle is modelled as a body with a single degree of freedom (DOF) along the track curvilinear abscissa.

Numerous researchers have tried to integrate LTD and MB simulations while preserving the numerical efficiency of each module [8, 9]. One straightforward approach involves constructing an MB model supplemented with in-train forces derived from preliminary LTD simulations. This method is quick and requires a negligible effort to exchange data from the two simulation environments, but it does not capture the mutual interaction between the dynamic states solved by both codes. Nevertheless, Cantone et al. [10] proposed enhanced LTD simulation frameworks, employing simplified single DOF masses for most vehicles while fully modelling a select few, considering their full dynamics and the wheel-rail contact interaction. This approach, however, may strain the computational speed of the LTD numerical integrator. Nonetheless, this method is available within the Train3D module of the Universal Mechanism (UM) commercial code, which effectively uses Park's integrator for both LTD and MB modules [11]. Bosso et al. [12] tried the opposite strategy, building models with different levels of complexity for the vehicles in the train composition within an MB code. Nonetheless, they showed that this approach can result in numerical instabilities when analysing long trains, whilst being unpractical to build and manage.

To benefit from the strengths of both LTD and MB codes, co-simulation arises as a promising opportunity, enabling the application of independent numerical integrators with data exchange during simulation. Nevertheless, the requisite data exchange unavoidably prolongs calculations, with reported wall clock times 5 to 6 times higher than the straightforward method [13]. Furthermore, the accuracy and computational efficiency of co-simulation heavily rely on the sampling period, i.e., the time interval between successive data exchanges between LTD and MB codes.

This study benchmarks and compares the common co-simulation architecture with traditional modelling strategies combining LTD and MB models, focusing on simulation outputs and computational performances. Specifically addressing co-simulation, the paper seeks to explain the impact of sampling period selection on computation accuracy and stability. The paper is organised as follows. The Methods section describes the simulation case study, the MB model of the reference wagon and the strategies implemented to combine the codes, with great attention to co-simulation. The Results section focuses on the effect of the different modelling choices on the major simulation outputs, including the safety indexes calculated using detailed MB models. Finally, the Conclusions section discusses the primary outcomes of the activity, which can drive researchers to develop their numerical framework to consider the mutual dependency between LTD and MB simulations.

2 Methods

The co-simulation architecture is validated, compared, and tested against other modelling strategies considering the train 4 simulation scenario as defined in the international benchmark of LTD simulators [14, 15]. The train consist is made up of 2 head locomotives + 120 wagons + 1 remote locomotive + 120 wagons. The 4th benchmark train configuration is selected due to the similarity of its wagons with the iron ore freight wagons with three-piece bogies running in Brazil. The full dynamics of the 4 wagons behind the remote locomotive is studied with a detailed model implemented in the SIMPACK commercial MB code, while the rest of the train composition is modelled with different methods, with a primary focus on co-simulation. The reference track for the simulation is extracted from the benchmark dataset and it corresponds to the track section between the 27.5 and 32.9 km marks, where two left-handed curves are present. The first curve, with a radius of 200 m and superelevation of 160 mm, starts at the 28th km mark, while the second curve starts at the 32nd km mark, and it features a radius of 300 m with 120 mm superelevation. Both curves include an entry transition of 50 m followed by a full curve section of 300 m and then a final 50 m exit transition.

The reference vehicle in the MB model is a heavy-haul gondola wagon with two three-piece bogies. Each bogie model consists of two wheelsets, two side frames and a central bolster frame. The primary suspension (between the wheelset and the side frame) features a PAD element on the wheel adapter. The secondary suspension includes a pack of springs and two friction wedges with constant damping, supporting each side of the bolster load. The bolster has a centre plate for connection to the carbody, as well as two roller side bearings with 25.4 mm of gap acting as side support for the carbody rolling movement. The longitudinal connection between adjacent wagons of the four-car group is obtained with hysteresis force elements representing the behaviour of the draft gears. On each wagon, a force element acts on a follow-track marker located on top of the rail, in the contact height, to apply the resistant forces for rolling and curving, while the slope resistance is calculated by the MB code itself based on the track slope line. Each car has 11 bodies and 62 DOF. Hence, the four-car group has 248 DOF and 44 bodies. The bogies are adapted from a validated model published by scholars from Universidade Estadual de Campinas (UNICAMP) in different works [16 - 19] and the wagon, bogie and four-wagon setup are illustrated by Figure 1.

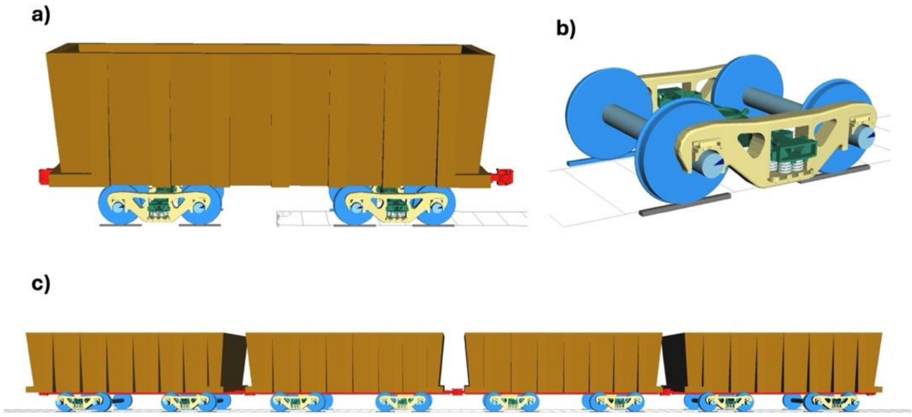

Figure 1: MB model: a) single heavy-haul wagon, b) detail of the three-piece bogie and c) the four-wagon setup built in this work.

The co-simulation architecture developed to combine LTD and MB simulations is based on the default SIMAT protocol available in SIMPACK, which enables the communication of a SIMPACK MB model with a SIMULINK model. The communication takes place via TCP/IP ports, with the SIMAT block requiring the definition and tuning of the so-called "sampling period", i.e., the inverse of the data exchange rate between the SIMPACK and SIMULINK codes. In this work, the SIMPACK model is demanded to calculate the full dynamics of the group of four wagons, while the SIMULINK model simulates the LTD of the remaining vehicles in the train, calculating all in-train forces. The SIMULINK model implements the in-house LTDPoliTo code [20, 21], written in MATLAB by the railway research group from Politecnico di Torino (PoliTo) in past activities. For co-simulation purposes, the LTDPoliTo code is integrated within the SIMULINK model as a compiled C-mex S-function. During the simulation, the SIMPACK model provides as outputs (*y-outputs*) the longitudinal position and speed of the four wagons and gets back the in-train forces at the front and back of the train composition as inputs (*u-inputs*), see Figure 2.

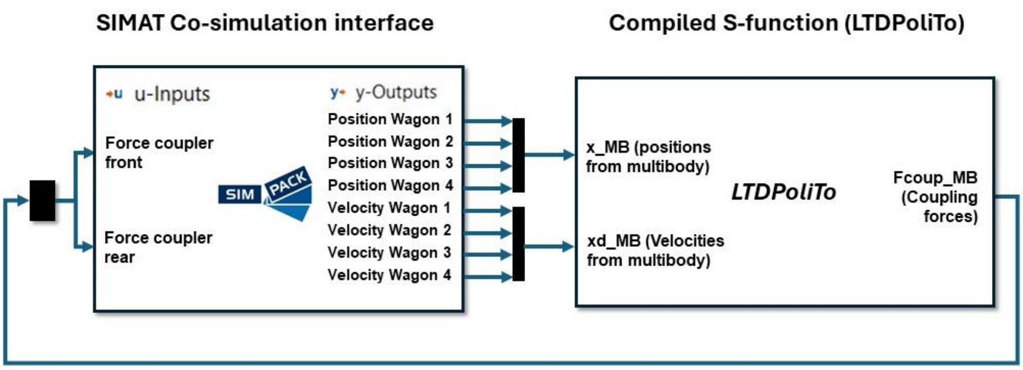

Figure 2: SIMPACK-SIMULINK co-simulation architecture based on SIMAT block (strategy d) in the rest of the paper).

The co-simulation architecture is benchmarked against other modelling strategies, namely i) the straightforward approach, that imports the in-train forces from a preliminary LTD standalone simulation, ii) an MB model using masses with a single DOF along the track curvilinear abscissa for the other vehicles in the train composition (mixed MB approach) and iii) a second MB model using a single big mass for blocks of wagons. The strategies considered in the paper are sketched in Figure 3, Table 1 shows the number of bodies and DOFs in the MB code for each modelling strategy, as well as letters ID to identify each strategy. Please note that strategy b) (mixed MB with single DOF vehicles) is like the one suggested by Bosso et al. [12], however in this work, each simplified vehicle is modelled as a single body with 1 DOF, while Bosso et al. used for each vehicle 3 bodies with 5 DOFs in total.

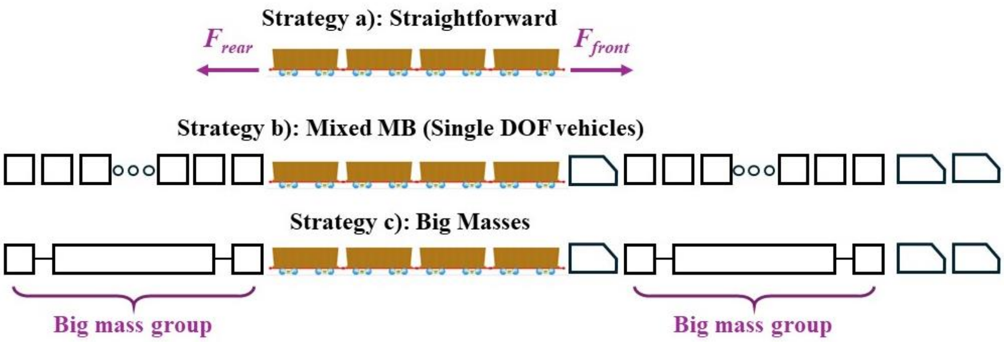

Figure 3: Modelling strategies proposed in this work for benchmarking of the co-simulation strategy.

Table 1 - Number of bodies and DOFs in the MB model for each strategy.

Strategy	Strategy ID	Number of bodies	Number of DOFs
Straightforward	a)	44	248
Mixed MB (single DOF vehicles)	b)	283	487
Big masses	c)	53	257
Co-simulation	d)	44	248

3 Results

The tested approaches described in the previous section are first validated considering the speed profile for the wagon behind the remote locomotive, i.e., the leading wagon of the group of detailed vehicles modelled in SIMPACK. For co-simulation, results are given for 3 values of sampling period, namely 1, 0.1 and 0.025 ms, corresponding to data exchange rates of 1, 10 and 40 kHz. In the co-simulation framework, the LTD equations are solved using the ode15s solver available in SIMULINK, setting the absolute and relative tolerance values to 10^{-6} and 10^{-8}, respectively. These tolerance values are far lower than the tolerances that could be used for pure standalone LTD computations, as preliminary simulations show that a good accuracy could be achieved with tolerances larger by 2 orders of magnitude. Nonetheless, when integrating the LTD code with MB simulations, the tolerances must be reduced to ensure the numerical stability of the method, although this approximately doubles the wall clock time for the simulation.

The speed profile (speed versus location on track) of the leading wagon of the group behind the remote locomotive is plotted in Figure 4 for the different tested methods. Figure 4 highlights that all approaches provide a similar speed profile except for co-simulation when the sampling period is set to 1 ms. As a matter of facts, when the sampling period is not small enough, both MB and LTD solvers can struggle to achieve convergence, and the values of in-train forces applied in front and at the rear of the wagons in the MB model cause discrepancies in the speed profile. Conversely, with smaller sampling periods, the speed profile is closer to the one achieved with the straightforward, mixed MB and big mass MB model strategies.

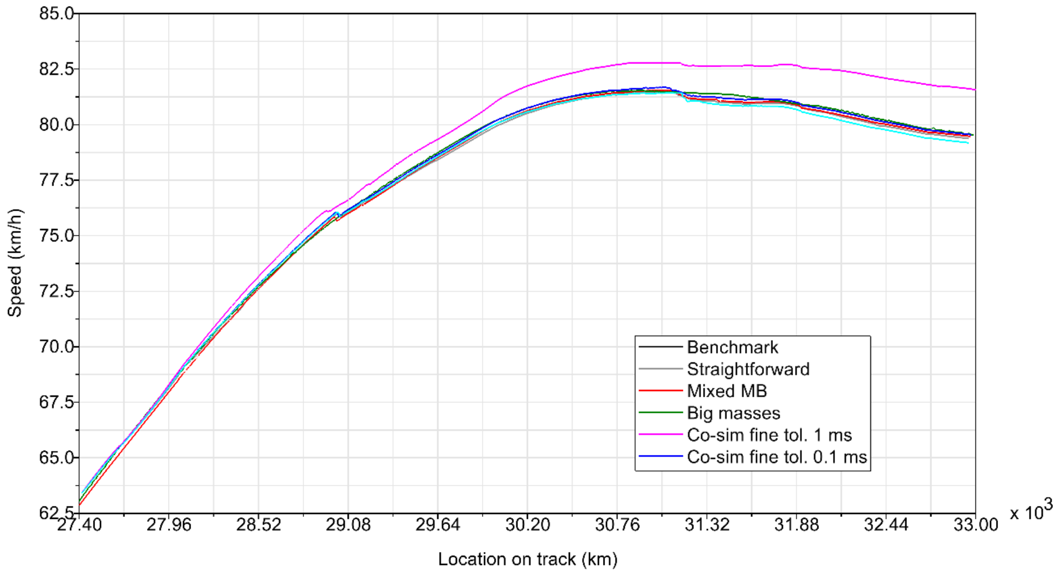

Figure 4: Speed profile for the leading wagon of the group.

As already stated, all strategies can be used to evaluate the wheel-rail contact forces and related running safety indexes on the wagons modelled in detail within the SIMPACK MB code. Figure 5 and Figure 6 show the values of the derailment coefficient (Y/Q) on the outer wheel of the leading wheelset of wagons 120 and 118, respectively, with vehicles numbered in ascending order from the train tail. Therefore, wagon 120 is the leading wagon of the group, i.e., the wagon behind the remote locomotive. In both Figure 5 and Figure 6, the left plot shows a zoom on the 200 m radius curve, while the plot on the right refers to the 300 m radius curves, where lower values of derailment coefficient are achieved due to the wider radius. For both curves and wagons, the results obtained with sampling period of 0.1 and 0.025 ms overlap each other, while the line corresponding to the 1 ms sampling period features different values, thus confirming that the 1 ms sampling period leads to inconsistent outputs.

Concerning wagon 120, see Figure 5, the derailment coefficient looks strongly affected by the modelling strategy, as the mixed MB and big mass models feature different values of the derailment coefficient with respect to the straightforward method and co-simulation architecture. This is due to the modelling of the in-train forces, as for the straightforward and co-simulation methods, the in-train forces obtained from the LTD module are applied along the track tangential direction only, thus acting as pure trailing forces. On the other hand, with the mixed MB and big mass models, the in-train forces are evaluated as point-to-point (Ptp) forces acting along the direction connecting the markers of adjacent coupling systems, thus producing lateral force components that affect the wheel-rail contact forces. For the 200 m curve, the mixed MB and big mass models are characterized by larger values of the derailment coefficient, while on the 300 m radius curve, they feature lower values. This is due to the different operating conditions, as on one curve the locomotives are providing traction, while on the other they are providing dynamic braking forces. Shifting focus to wagon 118, see Figure 6, the results are far less affected by the modelling strategy, as this vehicle is inside the four-wagon group, and the in-train forces are always calculated as Ptp force elements. For the reference operating conditions, with all modelling strategies, the derailment coefficient is well below the threshold limit of 0.8, thus ensuring that all strategies are valid for a preliminary evaluation of the derailment coefficient. However, the generation of lateral forces has a non-negligible impact on the computed safety index, hence more accurate investigations would require the development of detailed models of the wagon connection systems, with a consequent increase of the computational effort.

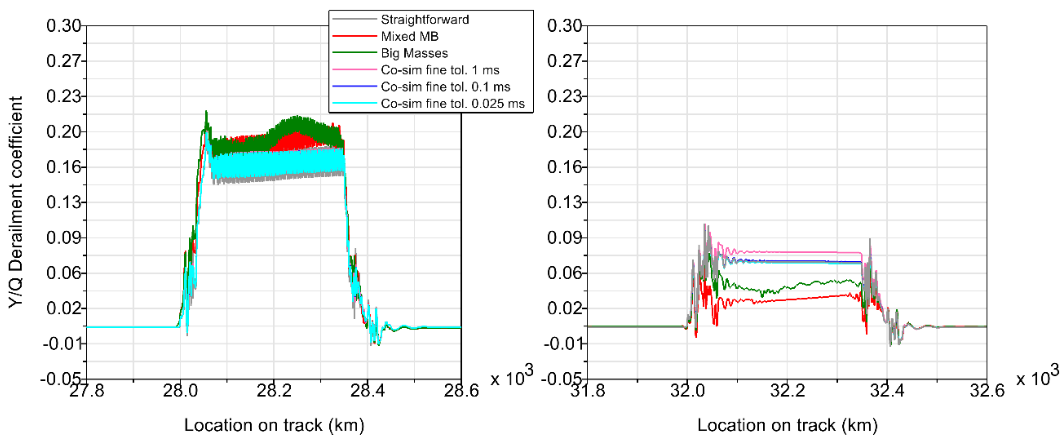

Figure 5 - Y/Q for outer wheel of leading wheelset on wagon 120.

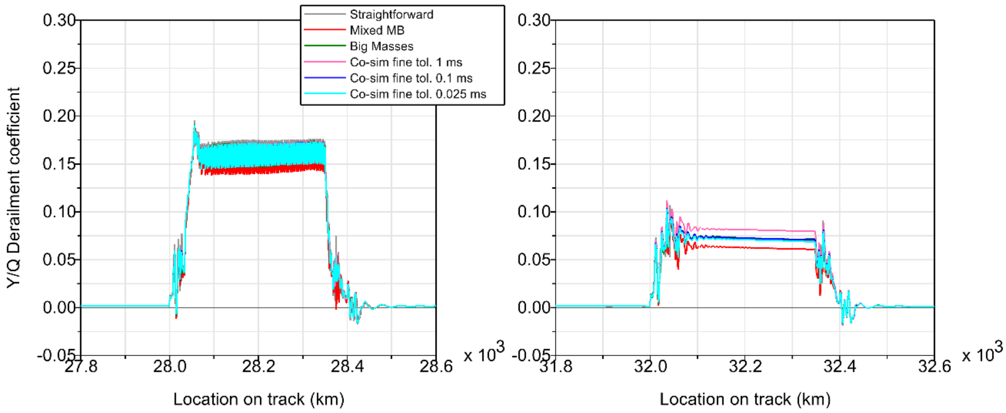

Figure 6 - Y/Q for outer wheel of leading wheelset on wagon 118.

The selection of the optimal strategy for the combination of LTD and MB modules cannot be made without an assessment of the computational performance. The tested strategies feature strongly different computational speeds, as it can be inferred from Table 2, which provides the CPU time, wall clock time and real-time (RT) factor recorded in the simulations. The RT factor is calculated as the ratio of the wall clock time over the simulated trip time, so that values below 1 mean that the simulation is faster than real-time. The simulated trip time is set to 260 s for all strategies, namely from time instant 2830 s to time instant 3090 s according to the benchmark outputs calculated with the LTDPoliTo code. All simulations are run on the same desktop computer setting 4 threads for the computation in the MB environment.

Table 2 - CPU time, Wall clock time and RT factor for each strategy.

Strategy	**CPU Time (s)**	**Wall clock time (s)**	**RT factor**
a) Straightforward	483.06	122.62	0.45
b) Single DOF bodies	3428.95	869.80	3.35
c) Big masses	761.98	198.59	0.58
d) Co-simulation (1 ms)	38677.3	14517.0	55.83
d) Co-simulation (0.1 ms)	36171.3	13364.3	51.40
d) Co-simulation (0.025 ms)	51386.8	20288.5	78.03

For the reference operation scenario, the co-simulation architecture proves to be at least 2 orders of magnitude slower than the straightforward approach relying on the application of in-train forces coming from a preliminary LTD simulation. When the sampling period is set to 0.1 ms, the simulation is faster than for sampling time of 1 ms. The explanation to this behaviour is that with a large sampling period, the solvers struggle to find convergence, thus leading to a larger number of rejected time-steps, which require computationally demanding evaluations of the system Jacobian and mass matrices. Moreover, with respect to the mixed MB model using a single DOF mass for each simplified vehicle in the composition, the co-simulation is more than 15 times slower. The development of MB models with big masses replacing sets of wagons has excellent computational performances, which are well comparable to the ones achieved with the straightforward approach. As a matter of facts, only the straightforward and big mass models are faster than real-time.

4 Conclusions and Contributions

Based on the results of this activity, it is believed that due to the longer wall clock times and to the time spent in tuning the sampling period and solver tolerances when implementing co-simulation, mixed MB models with 1 DOF simplified vehicles should be preferred. In fact, the tolerance sets determined with standalone LTD or MB simulations should be carefully refined when the two codes exchange data within co-simulation frameworks, although this leads to lower wall clock times. In addition to guaranteeing better computational efficiency, the mixed MB model can solve LTD and MB states within a single numerical environment, thus simplifying and speeding up post-processing operations. To further reduce the wall clock time, achieving real-time or faster than real-time computation, a good choice is represented by MB models replacing blocks of wagons with a single body featuring a large mass, although in this case, only a limited number of in-train forces can be properly calculated.

Furthermore, the models built within the MB environment and not relying on data exchange with the LTD module, can more easily account for the generation of lateral forces, which are shown to influence the derailment coefficient in the reference train operation, especially for the leading car of the group. To obtain more accurate and more reliable outputs, the MB models should be built in future works considering the detailed dynamics of the vehicle connection systems, for a proper evaluation of the lateral in-train force components.

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